A Standardized Approach to PV System Performance Model Validation

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Introduction

- PV performance models are used for prediction of expected energy production for project proposals
    - Evaluation of different designs (e.g., tracking vs. fixed, module technology, inverter, BOS) and locations.
- Many performance models available
    - Klise and Stein (2009) surveys available models
- Models are based on different conceptual approaches and implementations are not consistent.
- Results vary between models run for same system and weather.

Goals

- Develop a standard method for validating PV performance models in order to:
  - Increase confidence and understanding in model results
  - Identify areas for model improvements, gaps in existing data, and sources of modeling error
  - Support consistent, well informed business decisions that will ultimately allow solar technology solutions to prosper.

PV Modeling Steps

- Read inputs:
  - Array design (module, string, inverter, mounting, tracking, ground cover, etc.)
  - Weather (irradiance, temperature, wind speed, etc.)
- Translate irradiance to plane-of-array (POA)
  - Sun position calculation, irradiance model
- Evaluate ‘effective’ irradiance
  - Angle on incidence effects
  - Spectral effects (air mass correlations or physics models)
- Determine cell temperature
- Calculate I_{mp}, V_{mp}, and P_{mp}
- Estimate and apply derates (soiling, DC loses, mismatch, array utilization, etc)
- Model inverter performance (P_{ac})

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Model Validation Process

- Develop data sets including system description, weather data and performance data for multiple technologies, applications, and climates.
  - Understand and document data uncertainty
- Provide the system description and weather data to modelers, who will model the system and provide results.
  - Fully document model parameters and assumptions
- Apply a unified mathematical/statistical approach for comparing measured and modeled quantities and document comparisons in a standardized reporting format.
  - Propagate uncertainties, if possible
- Identify opportunities for model improvement

Mathematical/Statistical Approach

- Identify quantities for validation
  - DC + AC power, POA irradiance, module temperature, etc.
- Calculate model residuals (Residual = modeled values – measured value)
  - Calculate summary statistics (R^2, RMSE, MBE, annual bias, etc.)
  - Plot residuals vs. time
  - Plot distribution of residuals
  - Test correlation between residuals and other variables
- Residuals from a valid model will be as small as possible and randomly distributed

Example Application of Validation Approach

- 1 kW DC, m-SI, fixed latitude tilt, photovoltaic system in Albuquerque, NM
  - 1 year of hourly-averaged weather and performance data collected at site.
    - GHI, DNI, DHI, air temperature, wind speed (multiple instruments)
    - DC (and AC) current and voltage, module temperature

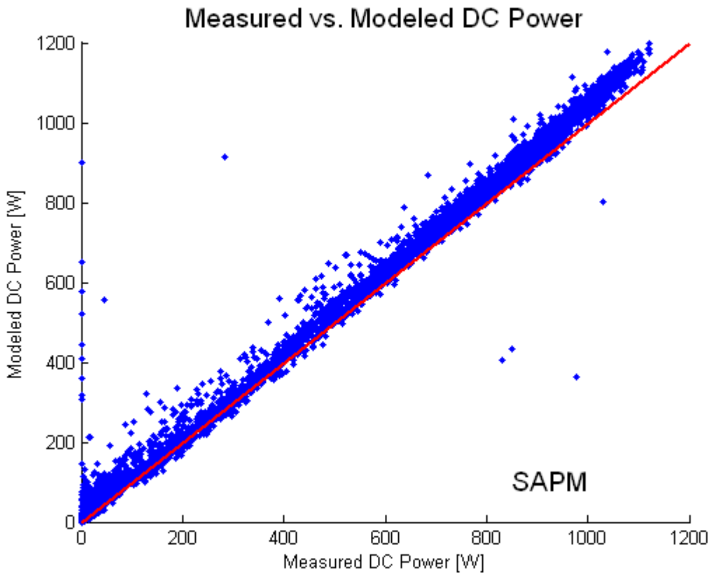
- Run two performance models in Solar Advisor Model (SAM)
  - Sandia PV Array Performance Model (SAPM)
  - CEC 5-Parameter Model (Univ. of Wisconsin)
- Set derate factors to zero

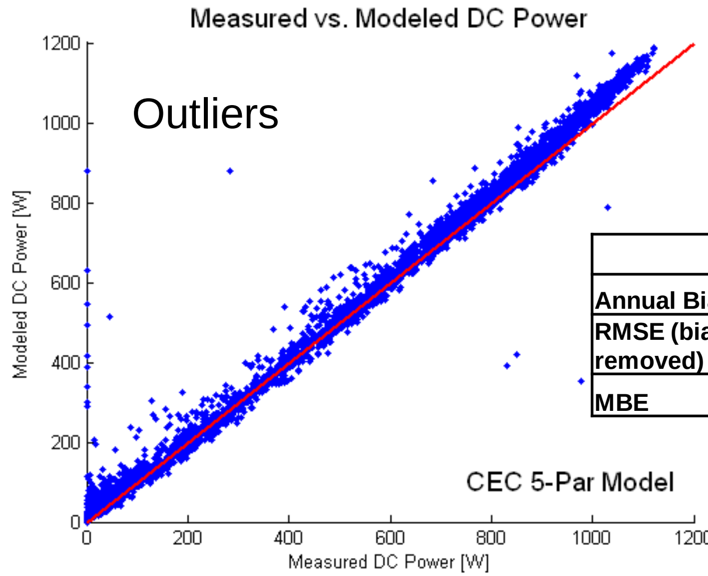
Sandia's Outdoor Test Facility

Inverter and DAS Configuration

Comparison of DC Power

- Measured vs. Modeled looks nearly identical
- Slight difference in bias error
  - Annual bias is same magnitude as typical derate factor
- Is there a fundamental difference between the models???





	SAPM	CEC 5 Par
Annual Bias	5.6%	3.3%
RMSE (bias removed)	26 W	23 W
MBE	27 W	16 W

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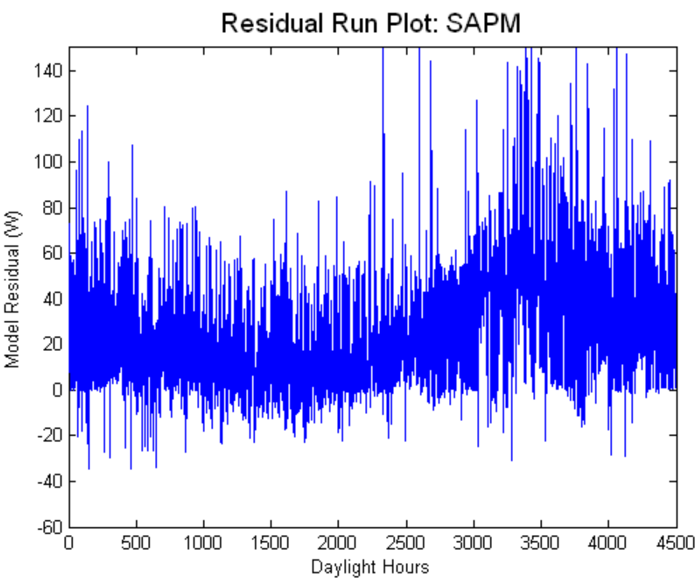
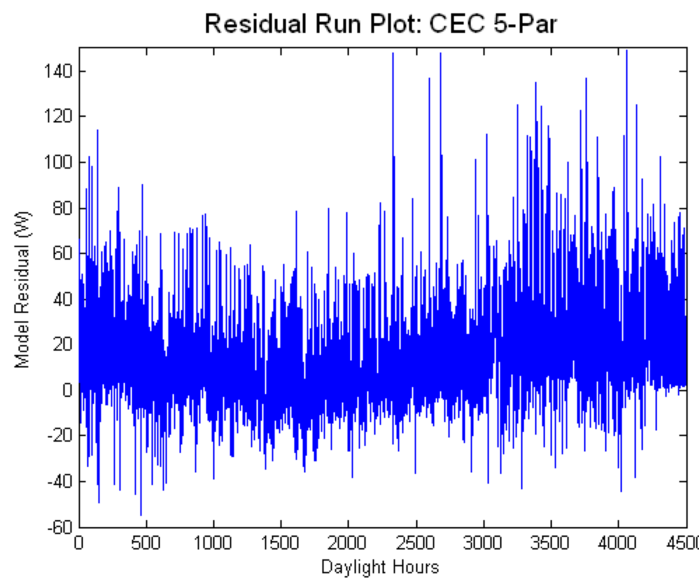
Residual vs. Time

- Period is from April 2007 to March 2008
- Outlier (-150<R<150 W) and night time data are removed
  - Outliers due to snow on sensor and array
- Sustained jumps in residuals may indicate soiling/cleaning cycles
- Differences between the model begin to appear.





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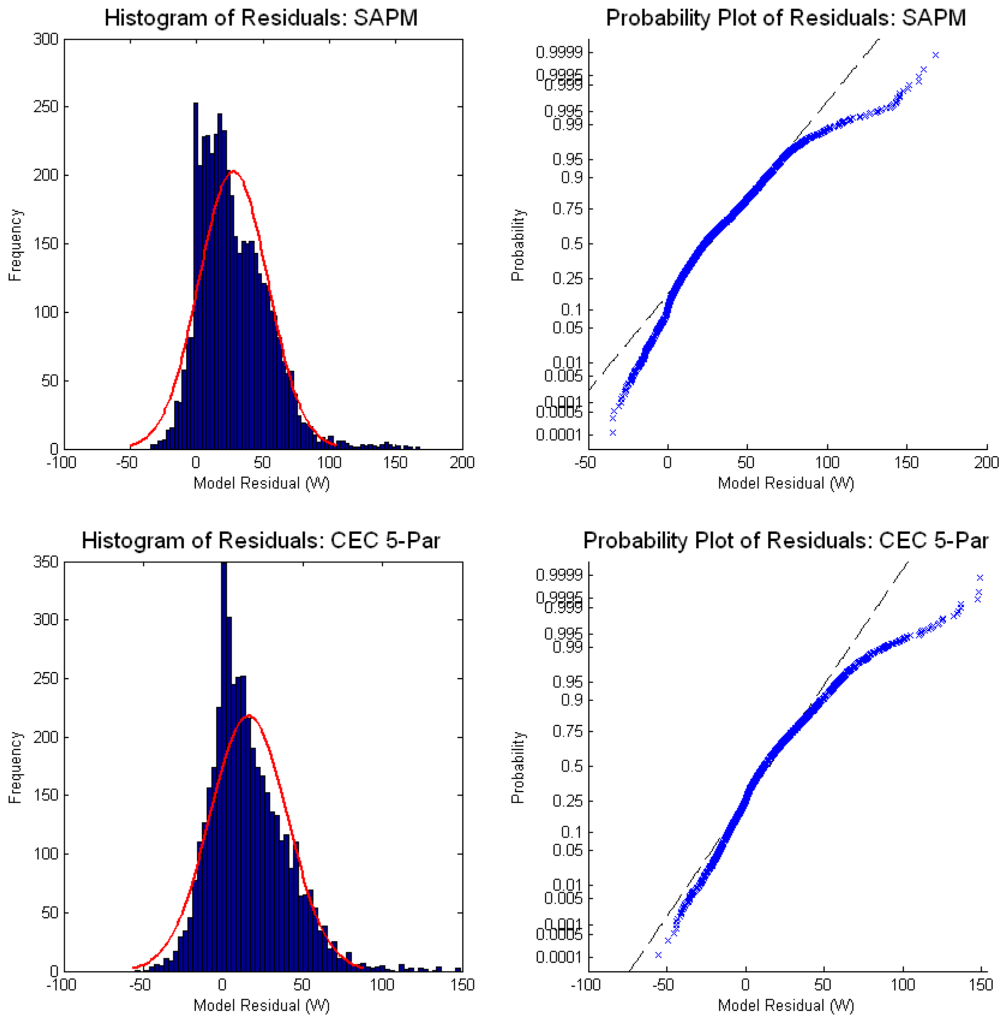
Residual Distributions



Both models have residuals that appear quite normal

Slight left skewness due to concentration of near zero residuals and a positive mean residual (no derate)

Residual Correlations

- Residuals are differences (model – measured)
- Residuals from a ‘Perfect’ model will be randomly distributed and uncorrelated with input variables.
- Residual analysis identifies any correlations if they exist.
  - These represent potential ‘flaws’ in the model and/or parameters.
- Stepwise regression allows variables which affect residuals to be indentified and ranked.

$$Y = b_0 + \sum_{j=1}^{P} b_j X_j$$

Y = dependent variables
X = P vectors of independent variables
b = linear regression coefficients

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Stepwise Results

- Stepwise regression was run for each model
    - Variables examined include incident beam, diffuse, and total radiation, air temperature, wind speed, sun zenith and azimuth angles, angle of incidence, and air mass
- Incremental R^2 value is the fraction of the residual variance explained by the correlation with the variable identified (in order of influence)

SAPM residuals most correlated with air temperature (18% of variance)
CEC 5-Par residuals most correlated with incident beam radiation (12% of variance)

SAPM			
Order	**Variable**	**R^2**	**Incremental R^2**
1	Temp	0.18	0.18
2	Incident Tot	0.35	0.17
3	Azimuth	0.37	0.02
4	Zenith	0.39	0.02
CEC 5-Par			
Order	**Variable**	**R^2**	**Incremental R^2**
1	Incident beam	0.12	0.12
2	Temp	0.22	0.10
3	WS	0.27	0.05
4	Azimuth	0.28	0.01

39% of SAPM variance explained

28% of CEC 5-Par variance explained

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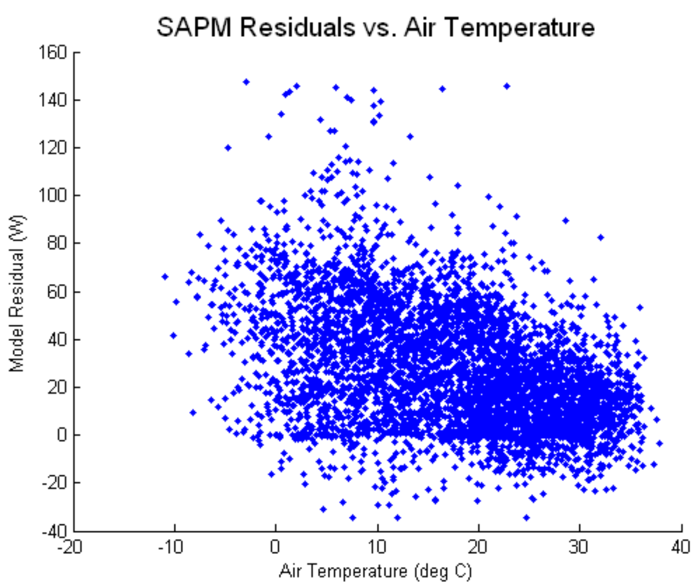
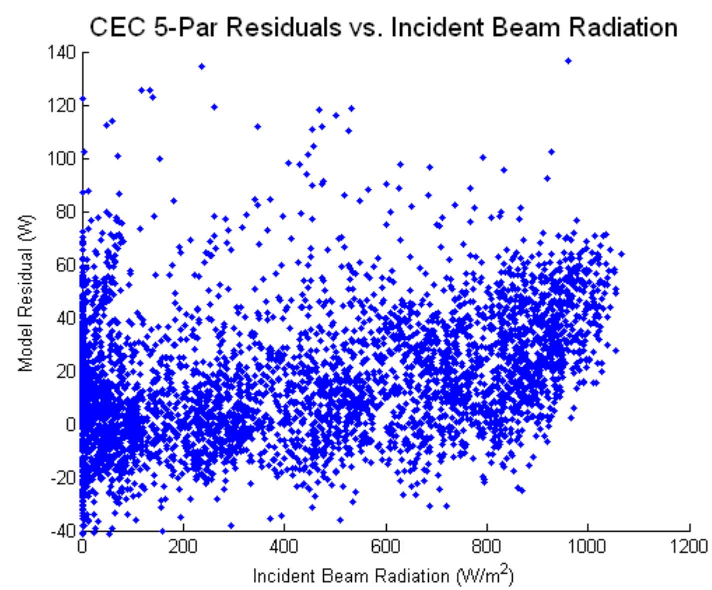
Primary Variable Correlations

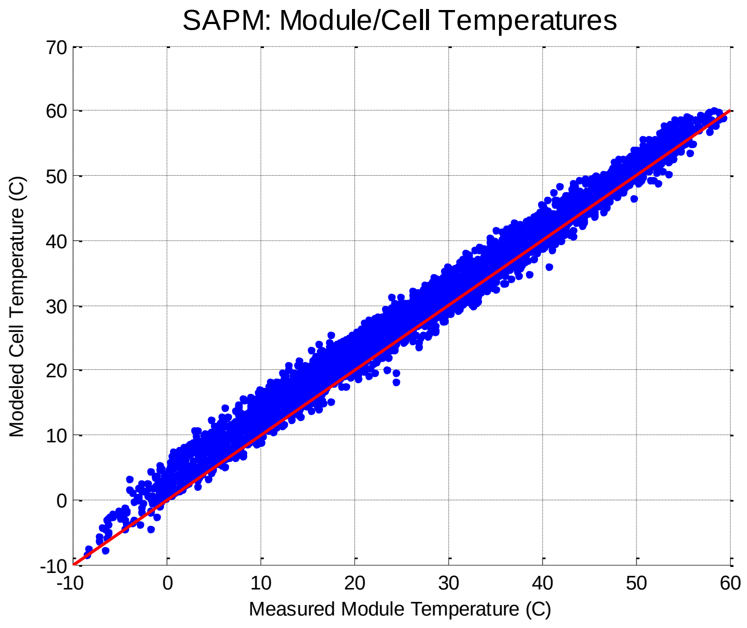
- SAPM residual correlation with air temperature suggests:
  – Module temperature coefficients need to be adjusted <u>or</u> cell temperature model needs to be improved.
- CEC 5-Par residual correlation with incident beam radiation
  – Still investigating this correlation





Module Temperature Model

- **Module temperature model appears to work well for this rack-mounted system.**
- **Module temperature coefficients likely need to be adjusted.**



Ongoing Work

- Collection of performance and weather data from more systems is needed.
  - Selection of different technologies
  - Diverse locations
  - Multiple configurations
- Side-by-side comparisons are important because weather data is similar and measurement accuracy is consistent across systems.
- Sandia National Laboratories will publish reference data sets for validation.
- Sponsor workshop this fall/winter on PV performance modeling
  - Participants simulate a reference system
  - Comparison of results from various models

Summary

- A standardized model validation approach has been developed with input from industry partners.
  - Based on residual analysis
  - Provides valuable information for model developers
- Provided an example application of the approach
- Next steps include:
  - collection of data from a representative range of technologies, climates, and designs
  - Model validation report (template?)
- PV modeling workshop being planned for end of 2010.

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THANK YOU